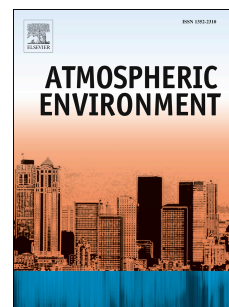


Accepted Manuscript

China's black carbon emission from fossil fuel consumption in 2015, 2020, and 2030

Yan Lu, Qin'geng Wang, Xiaohui Zhang, Yu Qian, Xin Qian



PII: S1352-2310(19)30247-X

DOI: <https://doi.org/10.1016/j.atmosenv.2019.04.032>

Reference: AEA 16660

To appear in: *Atmospheric Environment*

Received Date: 27 September 2018

Revised Date: 10 April 2019

Accepted Date: 13 April 2019

Please cite this article as: Lu, Y., Wang, Qin', Zhang, X., Qian, Y., Qian, X., China's black carbon emission from fossil fuel consumption in 2015, 2020, and 2030, *Atmospheric Environment* (2019), doi: <https://doi.org/10.1016/j.atmosenv.2019.04.032>.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1 China's black carbon emission from fossil fuel consumption in 2015,
2 2020, and 2030

3

4 Yan Lu^{a, b}, Qin'geng Wang^{a, c, *}, Xiaohui Zhang^a, Yu Qian^a, Xin Qian^{a, c}

5 ^a State Key Laboratory of Pollution Control and Resources Reuse, School of the Environment,
6 Nanjing University, Nanjing, 210023, China

7 ^b State Key Laboratory of Clean Energy Utilization, College of Energy Engineering, Zhejiang
8 University, Hangzhou, 310027, China

9 ^c Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment
10 Technology (CICAEET), Nanjing University of Information Science & Technology, Nanjing,
11 210044, China

12

13 * Corresponding author: Qin'geng Wang, School of the Environment, Nanjing University, Nanjing,
14 210023, China, Tel. /Fax: +86 25 89680530, E-mail address: wangqg@nju.edu.cn

15

16

Abstract: Black carbon (BC) emissions in China have been changing significantly due to rapid evolution of fuel consumption. In this study, BC emissions from fossil fuel consumption in different sectors were estimated in 2015 based on up-to-date activity data and emission factors (EFs). While for the future scenarios in 2020 and 2030, it was estimated according to relative changes in the activity level and EFs. In 2015, total BC emissions were estimated to be 1.48 Tg, mostly from the industrial, residential, and transportation sectors. Emission fluxes were found to have remarkable spatial features, where high fluxes generally located in eastern China. About 25% of the terrestrial area of China showed an annual flux above 0.2 t km^{-2} . Total BC emissions will be decreased to 1.33 (2020) and 1.16 Tg (2030). Most reduction will occur in the industrial and residential sectors, while the transportation sector will see an obvious increase. The dramatic reduction of BC emissions in future is a new indication to our current understanding of the emission and its effects as well, and it may provide guidance for future scientific research and policy making in the field of climate change and air quality control.

Keywords: BC; emission inventory; energy consumption; scenario projection

1. Introduction

Black carbon (BC), a product of the incomplete combustion of carbonaceous fuels, which can migrate globally via atmospheric circulation and international trade (Meng et al., 2018), has many effects on regional and global climate change (Cao et al., 2009; Flanner et al., 2007; Gu et al., 2010), as it can absorb solar radiation and act to heat the earth-atmosphere system (Andreae, 2001; Chung et al., 2005; Penner et al., 1998). In China, concern regarding BC has grown in recent years because of its role in enhancing haze pollution (Andersson et al., 2015; Ding et al., 2016). In addition, BC has been reported as a risk factor for human health, including higher blood pressure (Baumgartner et al., 2014), increasing the spread of infectious diseases (Wu et al., 2016), and increasing the risk of death (Li et al., 2016b).

Owing to its substantial energy consumption, China is estimated to contribute more than a quarter of global anthropogenic BC emissions (Bond et al., 2004; Li et al., 2017). China's total fossil fuel consumption amounted to 4.3 billion tons of coal equivalent (tce) in 2015, of which coal accounted for 63.7% (BP, 2017). According to the China Energy Statistical Yearbook (CNBS, 2015), 38.4% of the coal consumed was burned in power plants, 48.5% was burned in industrial boilers, and 2.0% was used as a household fuel. For the different application of coal, the BC emission factors (EFs, emission amount per unit of fuel used) are quite different (Streets et al., 2001).

The rapid development of China's economy has brought remarkable changes to the country's energy consumption. Besides marked changes to the total amount, great shifts have happened in the structure and efficiency of the energy consumption. From 1965 to 2015, China's annual energy consumption increased from 0.2 to 4.3 billion tce, while the proportion of coal decreased from 87.1 to 63.7% (BP, 2017). To reduce emissions of greenhouse gases (GHGs) and other air pollutants, China has determined to take increasing efforts in the next 15 years to control the consumption of fossil fuels. For example, as recently declared by the central government in the official paper "Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions", by 2030, the emission intensity (emission amount per unit of GDP) of CO₂ will decrease by 60–65% relative to the level in 2005, and that

non-fossil energy will account for 20% of total primary energy consumption. Under such fast-changing circumstances, many questions are to be answered, in particular, such as “what is the current status of BC emissions in China?”, “how will these emissions change in the future?” and “how certain are the estimations?”. Answers to these questions are fundamental for many studies aiming to better understand the effects of BC emissions on climate change, air quality, and human health.

Many studies have focused on BC emissions in China. For example, Streets et al. (2001) estimated the provincial BC emissions in China in 1995. Then they developed an inventory of air pollutant emissions for the year 2000, in which BC was included (Streets et al., 2003). After that, a series of emission inventories that include BC have been developed, focusing on emissions at different scales, such as in China (Lei et al., 2011; Qin and Xie, 2011; Wang et al., 2012), in Asia (Li et al., 2017; Ohara et al., 2007; Zhang et al., 2009), and globally (Bond et al., 2007; Bond et al., 2004; Lamarque et al., 2010). Those studies provided valuable information on BC emissions in China for different past periods. However, owing to the substantial changes in energy consumption that have occurred in the past decades, current status of China’s BC emissions has not been well reflected in previous studies. Furthermore, studies on future trends of China’s BC emissions are very rare. Streets et al. (2001) presented a projection for BC emission in China in 2020, based on data generated by the RAINS-Asia model. More recently, Wang et al. (2012) estimated BC emissions for the period 2008–2050 using activity data at a country level. However, owing to the limited number of studies and primitive data, the future BC emissions in China remains poorly understood.

In this study, China’s BC emission inventories are developed for 2015, 2020, and 2030, taking account of emissions from fossil-fueled power plants, industrial boilers, motor vehicles, and household coal-burning appliances. For the current state represented by the base year 2015, activity data are investigated for each type of sources at prefecture-city level (a total of 299 cities were considered). For future scenarios in 2020 and 2030, projections are made based on current state and relative changes in the activity level and the EFs. Future activity levels are determined

according to the Government's most recent Five-Year Plans (FYPs) and related studies. Current EFs are determined according to newly reported experimental work and adjusted to reflect technological developments in the future. Uncertainty is evaluated by the Monte Carlo method for the base-year inventory and discussed additionally for the future projections.

2. Methodology and data

2.1 Construction of the base year inventory

In general, BC emissions were estimated as a product of activity data and the corresponding EFs, using the following equation:

$$E = \sum_j \sum_k \sum_m A_{j,k,m} EF_{j,k}$$

where E is the total yearly emissions, g; A is the activity data, kg; EF is the emission factor, g/kg; and the subscripts *j*, *k*, and *m* represent a certain energy type, activity sector, and city, respectively.

Human activities were classified by sector into thermal power, industry, transportation, and residential. Fossil fuel energy such as coal, oil and natural gas were the fuels of interest. Coal was subdivided into raw coal, coke, briquettes, and washed coal. Oil was subdivided into kerosene, diesel, gasoline, and fuel oil. BC emissions were estimated at prefecture-city level for 28 provinces and municipalities, covering a total of 299 cities. For the other three provinces (Tibet, Qinghai, and Xinjiang), they were estimated at the provincial level because of a lack of city-level data. Activity data were collected from publicly available statistics that are published annually by different levels of government or official institutions. For example, energy consumption for most fuel types is reported in provincial statistical yearbooks. Detailed information on energy consumption of the four sectors, vehicle ownership, population, and GDP are published in city-level statistical yearbooks. The activity data for each of the provinces and sectors are summarized and presented in Table S1.

Corresponding to the activity sectors, EFs were distinguished as that of thermal power plants, industrial boilers, motor vehicles, and residential stoves. The fuel types

(raw coal, coke, briquettes, kerosene, diesel etc.) were considered separately. EFs were determined mainly based on previous inventory studies, with a few from reported measurements (Table S2). For the transportation and residential sectors, the EFs were determined according to reported measurements and values used in previous inventory studies. For the thermal power and industrial sectors, considering the greater changes in the removal efficiency, the EFs were mainly ascertained through revising original EFs (without considering control measures) with updated removal efficiencies. The removal efficiency of BC was determined by reference to $PM_{2.5}$, where BC mainly exists. The removal efficiencies of $PM_{2.5}$ in the thermal power and industrial sectors were determined as follows.

For the thermal power sector, conventional electrostatic precipitators are efficient in collecting large particle dusts over $10\text{ }\mu\text{m}$, but the removal efficiency of $PM_{2.5}$ was generally less than 90% (Chen, 2012). And Ye (2012) believed that the removal performance of $PM_{2.5}$ can reach 90% when the precipitators are reasonably designed. Therefore, the $PM_{2.5}$ (BC) removal efficiency in the thermal power sector was set at 90%, considering unorganized emissions. For the industrial sector, Li et al. (2016) adopted 50% removal efficiency to estimate emissions without considering the development status of baghouse. The dust removal facilities used in the industrial sector were mainly baghouses, which were used by 75% of the cement companies and 90–95% of the steel companies in 2015 (CAEPI, 2016). Therefore, the average removal rate of $PM_{2.5}$ (BC) of the industrial sector was assumed to be 75% in this study. The EFs used in this study and related references were listed in Table S2.

2.2 Projection of future emissions

BC emissions in 2020 and 2030 were estimated based on the current state in the base year and relative changes in the activity levels and the EFs (Table 1). Every 5 years, China's central and provincial governments formulate initiatives as successive FYPs for social and economic development. The most recent (13th) FYP was launched in March, 2016 and covers 2016–2020 (NDRC, 2016a). The government also launched a series of sectoral FYPs, such as for Electric Power Development (FYPEP)

(NDRC and NEA, 2016b), for Coal Industry Development (FYPCI) (NDRC and NEA, 2016a), and for Energy Development (FYPED) (NDRC and NEA, 2016c). In this study, the relative changes (or growth rates) in different sectors from 2016 to 2020 were directly obtained or inferred from these general and sectoral FYPs, at provincial and/or the country level. In cases where relative changes at a province could not be obtained, the values of similar provinces were adopted.

For the thermal power sector, the national growth rate of coal-fired power demand by 2020 was obtained from the 13th FYPEP, and we assumed the change rate between the 13th Five-Year and the period of 2020–2030 was consistent with that between the 12th and the 13th Five-Year. The efficiency of existing precipitators for thermal power is high, so EFs were assumed to remain stable in such period. The average annual growth rates of energy consumption in different provinces were determined according to related policies and planned measures as required in the regional 13th FYPCI (Table S3).

For industry, the national growth rate of coal consumption by 2020 was directly obtained from the 13th FYPEP, and we also assumed the change rate between the 13th Five-Year and the period of 2020–2030 was consistent with that between the 12th and the 13th Five-Year. As for the variations of the provinces, the growth of gross domestic product (GDP) was used as a surrogate factor, and the provincial growth rates of energy consumption for industry were calculated for 2015–2020 and 2020–2030 (Table S4).

For the transportation sector, BC emissions in 2020 and 2030 were projected based on the emissions in 2015 and relative changes in both energy consumption and the EFs. It was estimated that the total motor vehicle population will reach 200 million in 2020 (MIIT, 2010) and 300 per thousand people in 2030 (TASRI, 2016). The national average annual growth rates of motor vehicle population were calculated to be 6.1% in 2015–2020 and 8.1% in 2020–2030 if only basing on the population projection from the National Population Development Plan (2016–2030). However, the average fuel consumption of new vehicles will gradually decline to 5.0 L/100 km by 2020 and to 4.0 L/100 km by 2025, and the amount of new energy vehicles will

account for more than 30% of the total quantity by 2025 (MIIT et al., 2017). According to these potential changes, the average annual growth rates of energy consumption of the transportation sector in 2015–2020 and 2020–2030 were estimated to be 5.5% and 5.3%, respectively. Meanwhile, most new energy vehicles rely on electricity coming from the thermal power sector, which has also been considered in the projection for this sector.

For regional distribution of vehicles, the target growth rate of per capita disposable income in the 13th FYP was adopted as a reference for 2015–2020. And the growth rate for 2020–2030 was predicted based on changes between the 12th and 13th FYP. In particular, the total number of vehicles in Beijing will exceed 6.3 million in 2020 according to the 13th FYP of Transportation Development in Beijing. The growth in Shanghai was assumed to be the same as that in Beijing since the two cities have adopted similar policy in issuance of new car licenses. Therefore, the average annual growth rate of energy consumption in the transportation sector of each province (municipality) in 2015–2030 was estimated and given in Table S5.

The amount of residential coal consumption is related to the national gasification proportion. The trend of residential coal was determined by assuming that the increase in gasification proportion leads to the equal decrease in coal-fired proportion. For 2020, the national gasification proportion was calculated to be 33.1% based on related predictions in the 13th FYPED and the National Population Development Plan, 2016–2030. The national gasification proportion in 2015 was calculated to be 30.8% based on the population of using natural gas. Hence, the residential coal consumption in 2016–2020 would fall by a cumulative 3.5%. For 2030, the national gasification proportion was assumed to reach 50%, which is the target of urban gasification proportion for 2020 (NEA et al., 2016). Therefore, the cumulative reduction rate of residential coal consumption from 2020 to 2030 was assumed to be 25.4%.

Determination of future EFs is a great challenge and few studies have focused on this issue. In this study, EFs of industrial and residential combustion were assumed to decrease in the future and were determined according to the potential technical improvements as suggested in the 13th FYPs and related policies. EFs of motor

vehicles were determined according to emission standards (MEP and AQSIQ, 2005, 2016) that will take effect in 2020 and 2030 for major vehicle types. The relative changes in EFs for different sectors from the base year to 2020 and 2030, respectively, are also presented in Table 1. Regional differences in EFs were not considered in this study. Given the development difference in regions, it may lead to certain spatial bias in emission.

3. Results and discussion

3.1 Current BC emissions in China

In 2015, the total BC emissions from fossil fuel consumption in China were estimated at 1.48 Tg. Contributions from the thermal power, industry, transportation, and residential sectors were estimated at 0.003, 0.93, 0.24, and 0.31 Tg, respectively. Industry was the biggest contributor to BC emissions in China in 2015, accounting for 62.8% of the total. The residential and transportation sectors accounted for 20.9% and 16.2%, respectively. The thermal power sector was the lowest contributor, accounting for 0.1%. The relative contributions of different sectors were notably different to those presented by previous studies (Table S6). For example, Streets et al. (2003) and Ohara et al. (2007) reported that the primary source of BC emissions was the residential sector, which accounted for more than 80% of the total emissions from fossil fuel consumption, with industry attributed only 9% of the total. Cao et al. (2006), Lei et al. (2011), Zhang et al. (2009), and Wang et al. (2012) also concluded that the residential sector was the biggest contributor, accounting for approximately half of all BC emissions with industry then attributed 30–40% of the total. The difference between these values and that presented in our work reflects the impact of substituting coal with natural gas in the residential sector in the past decade. For the residential sector, BC emissions mostly arose from the consumption of raw coal, which was usually used for space heating. For the transportation sector, diesel consumption dominated BC emissions and gasoline was only responsible for a small portion of the total. For the industrial and thermal power sectors, coal consumption was clearly the predominant source of BC emissions, while petroleum only attributed a small portion.

BC emissions from major sectors of each of the 31 provinces in 2015 are shown in Fig. 1. There was notable variation in the emissions from different provinces. Shanxi, Shandong, Hebei, and Henan had much higher emissions than other provinces, and they contributed 34.5% of the national total. Although industry and the residential were the main sources of the overall BC emissions, their relative contributions varied considerably in different provinces. For example, in Shandong, Shanxi, Jiangsu, and Inner Mongolia, the industry accounted for more than 70% of each province's total. Elsewhere, in Guangdong, Zhejiang, Shanghai, and Hainan, transportation was the dominant source, each accounting for more than 40%. In Beijing, Hebei, and Heilongjiang, the residential sector was the dominant source because large amounts of coal are consumed for heating during winter.

3.2 BC emissions in 2020 and 2030

China's BC emissions in 2020 and 2030 were estimated to be 1.33 and 1.16 Tg, respectively. Compared with the BC emission prediction from the GAINS model (IIASA, 2011), the total emission in the base year 2015 (1.48 Tg) in this study was similar to the results of the latest status quo in the GAINS model (1.42 Tg from the scenario of WEO2016_NPS_CLE and WEO2016_NPS_NFC). Our results in 2020 and 2030 are higher than those (1.21 Tg in 2020 and 0.75–0.94 Tg in 2030) predicted based on the new policies scenario from the World Energy Outlook 2017 (IEA, 2017), but are close to those (1.37 in 2020 and 1.07 Tg in 2030) predicted based on the 12th Five-Year Plan. It can be seen that the new policies scenario given by World Energy Outlook 2017 may be optimistic about China's BC emission control in the future, which also means that if China wants to achieve the emission reduction suggested by the new policies scenario, energy transition and pollution control should be further strengthened on the basis of existing policies.

Contributions of the different sectors in the 2015, 2020, and 2030 are shown in Fig. 2. The industrial and residential sectors would remarkable decrease in future emissions, while emission from transportation would gradually increase, especially in 2030. For the industrial sector, relative to 2015, emissions in 2020 and 2030 would

decline by 13.2 and 34.8%, respectively, and for the residential sector, the proportions were 15.4 and 45.4%. This large decrease in BC emissions can be attributed to several reasons such as the slowing growth of energy consumption and the declining proportion of coal use for domestic and small boilers. For the transportation sector, the increased proportions were 5.7 and 59.9%. However, BC emissions from the thermal power sector showed a trend of increasing in 2020 because more coal will be applied in electricity production, and the emission would decrease in 2030 because of more stringent control measures. Nonetheless, contribution of the thermal power sector to the total BC emission of the country is still relatively small.

The provincial BC emissions in 2015, 2020, and 2030 are summarized in Table 2 and a sectoral breakdown for each province in 2020 and 2030 is presented in Table S7. All the provinces showed a decrease in their total BC emissions from 2015 to 2020, while there were fluctuations between 2015 and 2030. For example, from 2015 to 2030, BC emissions would decrease by more than 30% in Beijing, Shanxi, Jilin, and Tibet. However, across the same period in Tianjin, Guangdong, Guangxi, Hainan, and Chongqing, the emissions were projected to increase. In Shanghai, Jiangsu, Hubei, Hunan, Sichuan, Guizhou, and Shaanxi, most of the decreases were projected to occur between 2015 and 2020, with smaller decreases than expected in the following decade. In view of different sectors, from 2015 to 2030, the industrial sector in Shanxi and Shandong would experience notable decreases in their BC emissions. The similar case would happen for the residential sector in Hebei and Shanxi.

3.3 High-resolution gridded distribution of BC emissions

To provide more detailed understanding about spatial distribution of BC emission fluxes, and to lay groundwork for future related studies, high-resolution gridded inventories of BC emissions were generated by reallocating the prefectural-city level emissions with appropriate surrogates. GDP was chosen as the surrogate for the industrial, transportation, and thermal power sectors, and population was chosen for the residential sector. The GDP and population datasets at 1 km × 1 km resolution were provided by the Data Center for Resources and Environmental Sciences at the Chinese Academy of Sciences (RESDC) (<http://www.resdc.cn>). Using

ArcGIS 10.2, the 10 km × 10 km distributions of the BC emission fluxes in 2015, 2020, and 2030 were obtained, as shown in Fig. 3.

In general, BC emission fluxes in eastern China were much higher than in western China. Large areas with high fluxes were located in the North China Plain, the Northeast Plain, the Yangtze River Delta, the Pearl River Delta, and the Sichuan Basin. This is because large-scale urban agglomerations have emerged in these areas, which have led to the concentration of inhabitants, vehicles, and industries. However, projections to 2020 and 2030 suggested that areas with such high fluxes would shrink significantly. To further examine the flux changes in future, the amounts of grid squares with different ranges of emission fluxes were analyzed for 2015, 2020, and 2030, respectively, in terms of absolute grid numbers and percentages of the total, and are shown in Fig. 4. The number of grid squares with annual fluxes above 0.2 t km⁻² decreased in the future projections. In 2015, 25% of the grid squares showed an annual BC emission flux greater than 0.2 t km⁻². By 2020 and 2030, this percentage would decrease to be 21 and 20%, respectively. However, the number of grids with an annual flux of 0.05–0.2 t km⁻² was relatively stable, and the number of grid squares with an annual flux below 0.05 t km⁻² was projected to increase.

3.4 Uncertainty Analysis

The Monte Carlo method (Sonnemann et al., 2003) was used to characterize the uncertainty associated with the estimated BC emissions in the base year. According to related studies (eg., IPCC, 2006; Zhao et al., 2011), a normal probability distribution was assumed for activity data, and a log-normal distribution was assumed for the EFs. The coefficient of variation (CV), calculated by dividing the standard deviation by the mean, was determined for each kind of activity data and EFs. For the EFs, the CVs were determined for different sectors and fuel types using previously reported data and are shown in Table S2. For the activity data, the CVs were simply assumed to be 5, 10, 16, and 20% for the thermal power, industrial, transportation, and residential sectors, respectively, according to Zhao et al. (2011). Monte Carlo simulations were performed using the Crystal Ball method (Gonzalez et al., 2004) for 10,000 iterations. Results indicated that the total emission was 1.38 Tg on average, and the emission

range with a 95% confidence interval (CI) was from 1.03 to 1.83 Tg. Thus, the uncertainty of the total emission at the 95% CI was estimated to be -25–33%. Sectoral uncertainties were also analyzed and found to be -58–108% for the thermal power sector, -32–45% for the industrial sector, -64–100% for the transportation sector, and -39–42% for the residential sector.

The uncertainties of the BC emissions estimated here were lower than those presented in previous studies. For example, Streets et al. (2003), Zhang et al. (2009), Cao et al. (2011) and Lei et al. (2011) reported the uncertainty of BC emissions in China using the error-transportation method as ± 484 , ± 208 , ± 76.2 , and $\pm 187\%$, respectively. Meanwhile, Lu et al. (2011), Zhao et al. (2011) and Zhang et al. (2013) calculated uncertainty using Monte Carlo simulations and reported results of -43–93, -25–136, and -54–180%, respectively. The narrower range presented here may be mainly attributed to the improvement of activity data and EFs. However, the improvement of EFs should be limited, given that the EFs adopted in this study are mostly from previous inventories instead of the latest measurement values. In addition, a sensitivity analysis indicated that EFs remained the most important factor affecting the inventory's uncertainty, contributing approximately 80% of the total variance. This implied that further improvements in the accuracy of the inventory require more reliable EFs, especially those that provide specific detail for regions, different sectors and fuel types.

The uncertainty in the future projections was simply evaluated by assuming gradual increase of CVs for both activity data and EFs. Based on the data availability, reliability and relevant assumptions, the annual growth rate of CVs for activity data was assumed to be 5% (2020) and 10% (2030), respectively, compared to 2015. The uncertainty of EFs should be higher because of a lot of unpredictable factors in pollution control policies and technologies, and the annual growth rate of CVs for the EFs was assumed to be 15% from 2015 to 2030. On this basis, the uncertainty of the projection was estimated to be -41–65% for 2020, and -87–305% for 2030.

4. Conclusions

A more accurate BC emission inventory at a resolution of 10 km × 10 km for China in 2015 was established with updated prefecture-level statistical data and EFs. Effort was also made, for the first time, to forecast the provincial-level BC emissions for 2020 and 2030. National BC emission from energy consumption was 1.48 Tg (95% CI: -25–33%) in 2015, and was projected to be 1.33 (95% CI: -41–65%) and 1.16 Tg (95% CI: -87–305%) in 2020 and 2030. The industrial and residential sectors would remarkable decrease in future emissions, while emission from transportation would gradually increase, especially in 2030.

The significant changes in China's BC emission may have many implications for researchers and policymakers, and requires more attention in future studies. Previous studies suggested that the BC emission would play an important role in the climate change as well as air quality, by means of complicated non-linear interactions. For example, Li et al. (2016a) quantified the contributions from domestic emission sectors and emissions outside of China to concentration and direct radiative forcing of BC in China, and suggested that averaged over all of China, the all-sky direct radioactive forcing of BC at the top of the atmosphere was 1.22 W m⁻² in 2010. Mixed with other anthropogenic aerosols (sulfate, nitrate, and organic carbon), Zhuang et al. (2013) suggested that the value could be -0.78–-0.61 W m⁻². However, these studies were based on scenarios with BC emissions is much higher than estimations in this study. This implies that the current understandings about the effects of the BC emissions need to be further assessed, for both current state and future scenarios.

Continuous efforts on the emission reduction are necessary since the total emission is still huge and will act as a major factor affecting the environment in a long time. Spatial attentions should be paid on the North China Plain, the Northeast Plain, the Yangtze River Delta, the Pearl River Delta, and the Sichuan Basin, where emission intensities will remain high in the coming decades. Generally, emphasis should be placed to the residential in northeast China, the industrial in central-eastern China, and the transportation in southeast China, since they are dominant sources in the respective regions.

There is still large uncertainty in the present estimations of BC emission in China.

Some other sources other than fossil fuel combustion, such as fires, coke production, residential biomass burning, were not considered in this study, which could also lead to substantial BC emissions. Further studies are necessary to improve the understandings about the emission and the effects as well. With regard to the emission estimation, special efforts should be taken to improve the EFs. In particular, more reliable, in-situ experiment-based EFs are needed, especially those for different applications of fossil fuels.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2016YFC0208504), the National Key Basic Research Program of China (2014CB441203), the National Nature Science Foundation of China (41175129) and the Program B for Outstanding PhD Candidate of Nanjing University.

References

- Andersson, A., Deng, J., Du, K., Zheng, M., Yan, C., Skold, M., Gustafsson, O., 2015. Regionally-varying combustion sources of the January 2013 severe haze events over eastern China. *Environ. Sci. Technol.* 49, 2038-2043.
- Andreae, M.O., 2001. The dark side of aerosols. *Nature* 409, 671-672.
- Baumgartner, J., Zhang, Y., Schauer, J.J., Huang, W., Wang, Y., Ezzati, M., 2014. Highway proximity and black carbon from cookstoves as a risk factor for higher blood pressure in rural China. *Proc. Natl. Acad. Sci. USA* 111, 13229-13234.
- Bond, T.C., Bhardwaj, E., Dong, R., Jogani, R., Jung, S., Roden, C., Streets, D.G., Trautmann, N.M., 2007. Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000. *Global Biogeochem. Cy.* 21, 1-16.
- Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.-H., Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.* 109, 1-43.
- BP, 2017. BP statistical review of world energy.
- Cao G.L., Zhang X.Y., Gong S.L., An X.Q., Wang Y.Q., 2011. Emission inventories of primary

- particles and pollutant gases for China. Chinese Science Bulletin 56, 781-788.
- Cao G.L., Zhang X.Y., Wang Y.Q., Che H.Z., Chen D., 2006. Inventory of black carbon emissions from China. *Advances in Climate Change Research* 2, 259-264. (In Chinese)
- Cao J.J., Zhu C.S., Chow J.C., Watson J.G., Han Y.M., Wang G.H., Shen Z.X., An Z.S., 2009. Black carbon relationships with emissions and meteorology in Xi'an, China. *Atmos. Res.* 94, 194-202.
- Chen X.L., 2012. Discussion on treatment technology of PM_{2.5} emission in thermal power plants. *China Environment Protection Industry* 7, 26-29. (In Chinese)
- China Association of Environmental Protection Industry (CAEPI), 2016. Development report on baghouse industry in 2015, *China Environmental Protection Industry* 10, 5-20. (In Chinese)
- Chung, C.E., Ramanathan, V., Kim, D., Podgorny, I.A., 2005. Global anthropogenic aerosol direct forcing derived from satellite and ground-based observations. *J. Geophys. Res.* 110, 1-17.
- Department of Energy Statistics and National Bureau of Statistics (CNBS) , 2015. *China Energy Statistical Yearbook*. Beijing: China Statistics Press.
- Ding, A.J., Huang, X., Nie, W., Sun, J.N., Kerminen, V.M., Petäjä, T., Su, H., Cheng, Y.F., Yang, X.Q., Wang, M.H., Chi, X.G., Wang, J.P., Virkkula, A., Guo, W.D., Yuan, J., Wang, S.Y., Zhang, R.J., Wu, Y.F., Song, Y., Zhu, T., Zilitinkevich, S., Kulmala, M., Fu, C.B., 2016. Enhanced haze pollution by black carbon in megacities in China. *Geophys. Res. Lett.* 43, 2873-2879.
- Flanner, M.G., Zender, C.S., Randerson, J.T., Rasch, P.J., 2007. Present-day climate forcing and response from black carbon in snow. *J. Geophys. Res.* 112, 1-17.
- Gonzalez, A.G., Herrador, M.A., Asuero, A.G., 2004. Uncertainty evaluation from Monte-Carlo simulations by using Crystal-Ball software. *Accreditat. Qual. Assur.* 10, 149-154.
- Gu, Y., Liou, K.N., Chen, W., Liao, H., 2010. Direct climate effect of black carbon in China and its impact on dust storms. *J. Geophys. Res.* 115, 1-12.
- International Energy Agency (IEA), 2017. *World Energy Outlook 2017*. Available at: <https://www.iea.org/weo2017/>
- International Institute for Applied Systems Analysis (IIASA), 2011. *Greenhouse Gas and Air Pollution Interactions and Synergies model (GAINS)*, Laxenburg, Austria. Available at: <http://gains.iiasa.ac.at/gains/docu/GCC/index.menu>
- IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

- Lamarque, J.F., Bond, T.C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mievile, A., Owen, B., Schultz, M.G., Shindell, D., Smith, S.J., Stehfest, E., Van Aardenne, J., Cooper, O.R., Kainuma, M., Mahowald, N., McConnell, J.R., Naik, V., Riahi, K., van Vuuren, D.P., 2010. Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmos. Chem. Phys.* 10, 7017-7039.
- Lei, Y., Zhang, Q., He, K.B., Streets, D.G., 2011. Primary anthropogenic aerosol emission trends for China, 1990–2005. *Atmos. Chem. Phys.* 11, 931-954.
- Li, K., Liao, H., Mao, Y., Ridley, D.A., 2016a. Source sector and region contributions to concentration and direct radiative forcing of black carbon in China. *Atmos. Environ.* 124, 351-366.
- Li, M., Zhang, Q., Kurokawa, J.-i., Woo, J.-H., He, K., Lu, Z., Ohara, T., Song, Y., Streets, D.G., Carmichael, G.R., Cheng, Y., Hong, C., Huo, H., Jiang, X., Kang, S., Liu, F., Su, H., Zheng, B., 2017. MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP. *Atmos. Chem. Phys.* 17, 935-963.
- Li, R.P., Wu, L., Mao, H.J., He, J.J., Jing, B.Y., Zou, C., 2016. Establishment of an air pollutant emission inventory for Langfang urban area. *Acta Scientiae Circumstantiae* 36, 3627-3534. (In Chinese)
- Li, Y., Henze, D.K., Jack, D., Henderson, B.H., Kinney, P.L., 2016b. Assessing public health burden associated with exposure to ambient black carbon in the United States. *Sci. Total Environ.* 539, 515-525.
- Lu, Z., Zhang, Q., Streets, D.G., 2011. Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010. *Atmos. Chem. Phys.* 11, 9839-9864.
- Meng, J., Liu, J., Yi, K., Yang, H., Guan, D., Liu, Z., Zhang, J., Ou, J., Dorling, S., Mi, Z., Shen, H., Zhong, Q., Tao, S., 2018. Origin and radiative forcing of black carbon aerosol: production and consumption perspectives. *Environ. Sci. Technol.* 52, 6380-6389.
- Ministry of Environmental Protection of the People's Republic of China, General Administration of Quality Supervision, 2005. Limits and measurement methods for emissions from light-duty vehicles (III, IV). GB 18352.3-2005. China Environmental Science Press, Beijing, China.

- Ministry of Environmental Protection of the People's Republic of China, General Administration of Quality Supervision, 2016. Limits and measurement methods for emissions from light-duty vehicles (China 6). GB 18352.6-2016. China Environmental Science Press, Beijing, China.
- Ministry of Industry and Information Technology of the People's Republic of China, 2010. Ministry of Industry and Information Technology of the People's Republic of China estimates that China's car ownership will exceed 200 million in 2020. www.people.com.cn, Beijing.
- Ministry of Industry and Information Technology of the People's Republic of China, National Development and Reform Commission, Ministry of Science and Technology of the People's Republic of China, 2017. Medium- and Long-term Development Plan for the Automotive Industry. Available at <http://www.miit.gov.cn/n1146290/n4388791/c5600433/content.html>
- National Development and Reform Commission, 2016a. The 13th Five-Year Plan for Economic and Social Development of the People's Republic of China. Available at http://www.gov.cn/xinwen/2016-03/17/content_5054992.htm
- National Development and Reform Commission, 2016b. The National Population Development Plan (2016–2030). Available at http://www.gov.cn/zhengce/content/2017-01/25/content_5163309.htm
- National Development and Reform Commission; National Energy Administration, 2016a. The 13th Five-Year Plan for Coal Industry Development. Available at http://www.ndrc.gov.cn/fzgggz/fzgh/ghwb/gjjgh/201706/t20170605_850004.html
- National Development and Reform Commission; National Energy Administration, 2016b. The 13th Five-Year Plan for Electric Power Development. Available at <http://cape.ndrc.gov.cn/zcfg/201701/P020170112341246054484.pdf>
- National Development and Reform Commission; National Energy Administration, 2016c. The 13th Five-Year Plan for Energy Development. Available at http://www.gov.cn/xinwen/2017-01/17/content_5160588.htm
- National Energy Administration (NEA), Development Research Center of the State Council, (DRC), Ministry of Natural Resources of the People's Republic of China, (MNR), 2016. China Natural Gas Development Report 2016, Beijing.
- Ohara, T., Akimoto, H., Kurokawa, J.-i., Horii, N., Yamaji, K., Yan, X., Hayasaka, T., 2007. An

- Asian emisison inventory of anthropogenic emission sources for the period 1980–2020. Atmos. Chem. Phys. 7, 4419-4444.
- Penner, J.E., Chuang, C.C., Grant, K., 1998. Climate forcing by carbonaceous and sulfate aerosols. Clim. Dynam. 14, 839-851.
- Qin, Y., Xie, S.D., 2011. Estimation of county-level black carbon emissions and its spatial distribution in China in 2000. Atmos. Environ. 45, 6995-7004.
- Sonnemann, G., Schuhmacher, M., Castells, F., 2003. Uncertainty assessment by a Monte Carlo simulation in a life cycle inventory of electricity produced by a waste incinerator. J. Clean. Prod. 11, 279-292.
- State Council of the People's Republic of China, 2016. National Population Development Plan (2016–2030). http://www.gov.cn/zhengce/content/2017-01/25/content_5163309.htm
- Streets, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., Klimont, Z., Nelson, S.M., Tsai, N.Y., Wang, M.Q., Woo, J.-H., Yarber, K.F., 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J. Geophys. Res. 108, 1-23.
- Streets, D.G., Gupta, S., Waldhoff, S.T., Wang, M.Q., Bond, T.C., Bo, Y., 2001. Black carbon emissions in China. Atmos. Environ. 35, 4281-4296.
- Tsinghua Automotive Strategy Research Institute, 2016. The motor vehicle population will reach 300 per thousand people in 2030. news.sina.com.cn, Beijing.
- Wang, R., Tao, S., Wang, W., Liu, J., Shen, H., Shen, G., Wang, B., Liu, X., Li, W., Huang, Y., Zhang, Y., Lu, Y., Chen, H., Chen, Y., Wang, C., Zhu, D., Wang, X., Li, B., Liu, W., Ma, J., 2012. Black carbon emissions in China from 1949 to 2050. Environ. Sci. Technol. 46, 7595-7603.
- Wu, X., Lu, Y., Zhou, S., Chen, L., Xu, B., 2016. Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. Environ. Int. 86, 14-23.
- Ye, Y.J., 2012. Study of decreasing PM_{2.5} emission from thermal power plant. Electric Power Construction 33, 49-52. (In Chinese)
- Zhang, N., Qin, Y., Xie, S., 2013. Spatial distribution of black carbon emissions in China. Chinese Science Bulletin 58, 3830-3839. (In Chinese)
- Zhang, Q., Streets, D.G., Carmichael, G.R., He, K.B., Huo, H., Kannari, A., Klimont, Z., Park, I.S., Reddy, S., Fu, J.S., Chen, D., Duan, L., Lei, Y., Wang, L.T., Yao, Z.L., 2009. Asian emissions

- 544 in 2006 for the NASA INTEX-B mission. *Atmos. Chem. Phys.* 9, 5131-5153.
- 545 Zhao, Y., Nielsen, C.P., Lei, Y., McElroy, M.B., Hao, J., 2011. Quantifying the uncertainties of a
- 546 bottom-up emission inventory of anthropogenic atmospheric pollutants in China. *Atmos.*
- 547 *Chem. Phys.* 11, 2295-2308.
- 548 Zhuang, B.L., Li, S., Wang, T.J., Deng, J.J., Xie, M., Yin, C.Q., Zhu, J.L., 2013. Direct radiative
- 549 forcing and climate effects of anthropogenic aerosols with different mixing states over China.
- 550 *Atmos. Environ.* 79, 349-361.

551

Table captions:

Table 1 Nationally averaged relative changes in activity level (Act. level) and EFs for different sectors from 2015 to 2020 and from 2020 to 2030, compared to 2015

Table 2 Provincial BC emissions in 2015, 2020, and 2030 (Gg)

Table 1 Nationally averaged relative changes in activity level (Act. level) and EFs for different sectors from 2015 to 2020 and from 2020 to 2030, compared to 2015

Sectors	Relative changes 2015–2020 (%)		Relative changes 2020–2030 (%)	
	Act. Level	EFs	Act. level	EFs
Thermal power	+22.2	–10.0	+39.4	–30.0
Industry	–4.9	–10.0	–8.2	–30.0
Transportation	+32.0	–20.0	+127.7	–30.0
Residential	6.1	–20.0	9.0	–50.0

Table 2 Provincial BC emissions in 2015, 2020, and 2030 (Gg)

Province	2015	2020	2030	Province	2015	2020	2030
Beijing	13.3	11.4	8.6	Hubei	46.7	43.2	42.5
Tianjin	13.8	13.2	14.7	Hunan	47.1	42.6	39.2
Hebei	111.8	99.0	79.7	Guangdong	41.2	39.3	45.1
Shanxi	150.8	128.8	96.4	Guangxi	15.4	14.7	16.6
Inner Mongolia	83.9	74.0	59.8	Hainan	2.3	2.2	2.7
Liaoning	73.3	64.2	53.9	Chongqing	23.4	22.4	25.2
Jilin	33.9	29.4	23.3	Sichuan	37.0	33.4	31.1
Heilongjiang	28.7	25.2	20.7	Guizhou	41.5	37.8	35.0
Shanghai	14.2	12.7	12.1	Yunnan	59.1	53.1	46.5
Jiangsu	57.0	51.5	46.9	Tibet	31.5	27.6	21.1
Zhejiang	31.5	29.3	30.4	Shaanxi	33.1	30.2	27.7
Anhui	59.9	53.8	47.4	Gansu	47.9	42.6	35.2
Fujian	19.4	18.2	19.3	Qinghai	8.3	7.6	6.9
Jiangxi	26.5	24.9	26.2	Ningxia	27.3	24.0	19.3
Shandong	142.5	126.9	109.1	Xinjiang	54.1	48.6	41.8
Henan	106.6	94.5	78.6	Total	1483.0	1326.3	1163.0

Figure captions:

Fig. 1. Provincial BC emissions from thermal power, industrial, transportation, and residential sectors in 2015.

Fig. 2. BC emissions from different sectors in China in 2015, 2020, and 2030.

Fig. 3. Geographic distribution of BC emission flux in (a) 2015, (b) 2020, and (c) 2030.

Fig. 4. Amount (absolute and percentage) of grid squares showing different ranges of BC emission fluxes in 2015, 2020, and 2030.

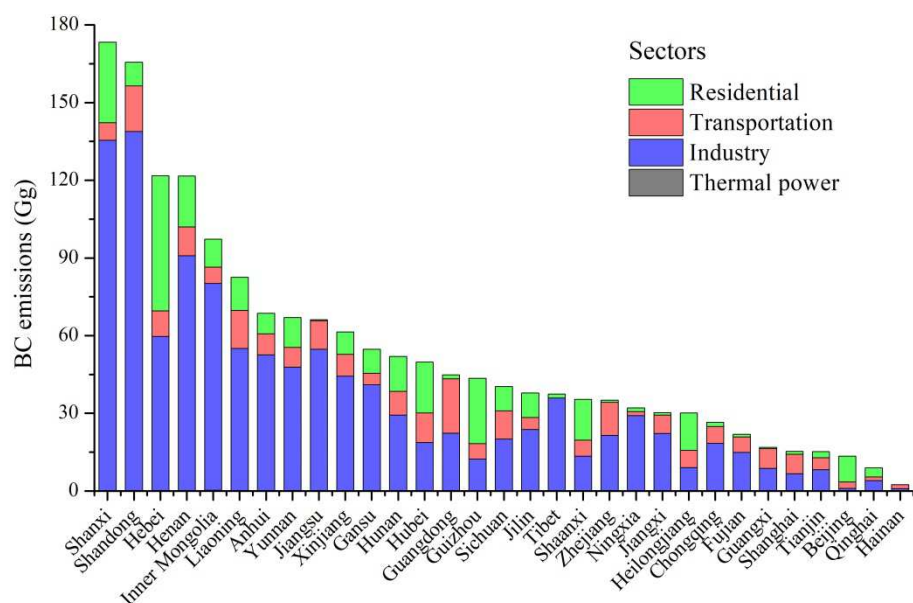


Fig. 1. Provincial BC emissions from thermal power, industrial, transportation, and residential sectors in 2015.

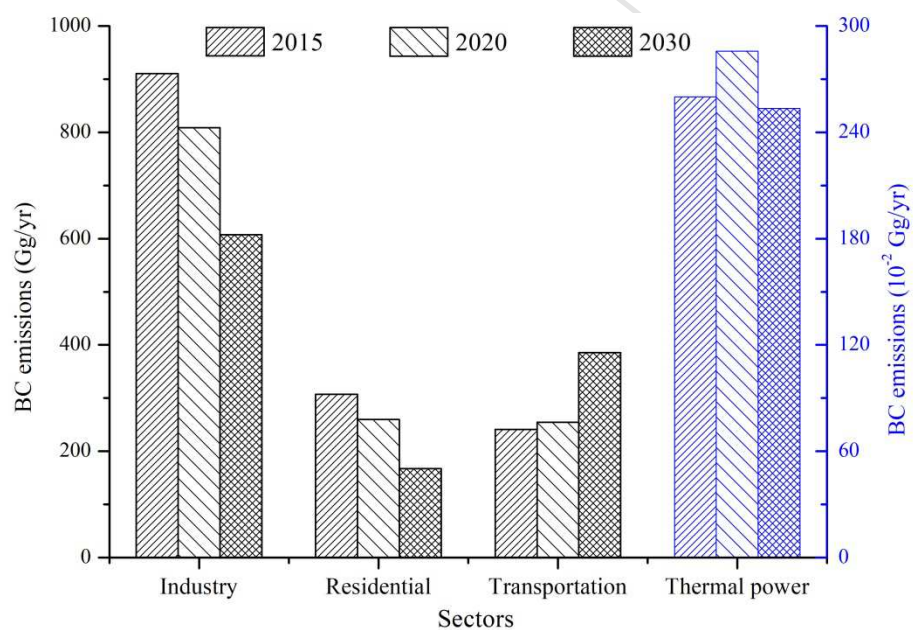


Fig. 2. BC emissions from different sectors in China in 2015, 2020, and 2030.

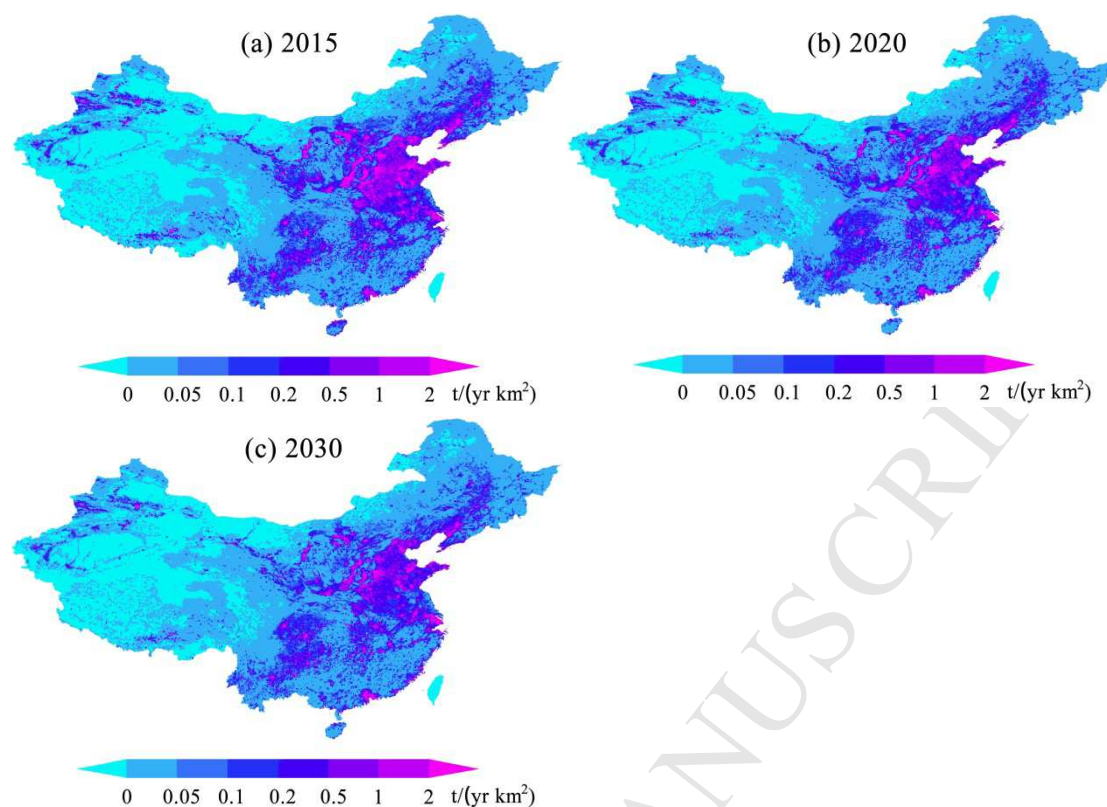


Fig. 3. Geographic distribution of BC emission flux in (a) 2015, (b) 2020, and (c) 2030.

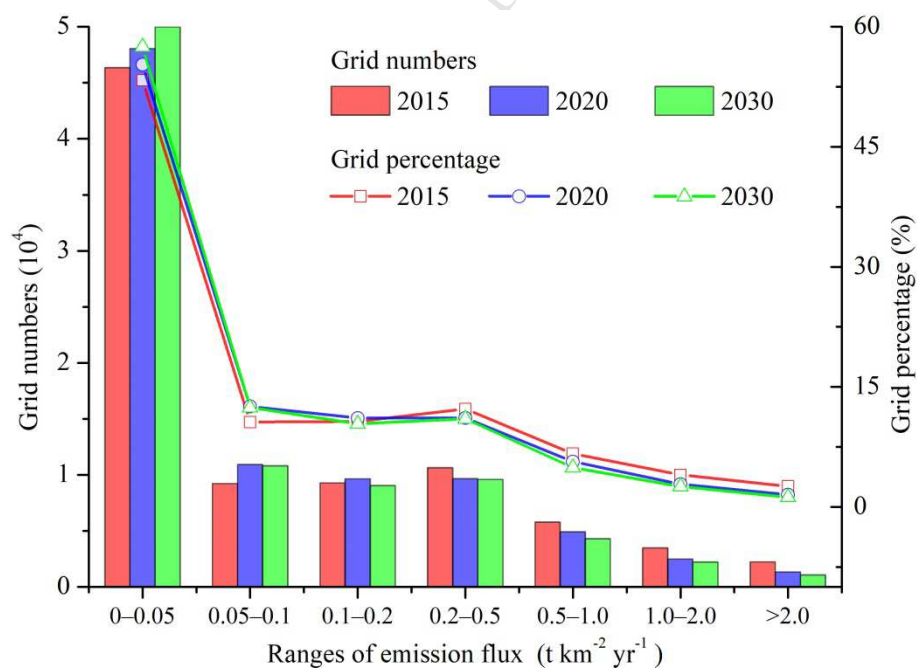


Fig. 4. Amount (absolute and percentage) of grid squares showing different ranges of BC emission fluxes in 2015, 2020, and 2030.

Highlights:

1. China's black carbon (BC) emissions have been changing significantly.
2. This study estimated BC emissions in 2015 and projected for 2020 and 2030.
3. National BC emissions are projected to decrease in the next 15 years.
4. Emissions from sectors show remarkable differences in growth.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: